THEORETICAL AND EXPERIMENTAL INVESTIGATIONS
OF COLLECTIVE MICROWAVE PHENOMENA IN SOLIDS

under the direction of
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ABSTRACT

I. MICROWAVE OSCILLATORS AND AMPLIFIERS BASED ON THE GUNN EFFECT

A. Experiments on High Efficiency Gunn Oscillators

The rf efficiency of a Gunn diode placed in series with a load resistance shunted by a shorted transmission line, one quarter wavelength long at half the domain transit frequency, is investigated experimentally. This simple configuration is shown to be capable, for the diodes used here, of 16.7% theoretical efficiency (33% with ideal diodes). Experimentally measured efficiencies of 15% at around 100 MHz are reported.

B. Measurement of the Space Charge Growth Rate in High Resistivity Gallium Arsenide

A possible two port unilateral microwave amplifier using the transferred electron effect in high resistivity ($\rho \approx 1000$ Ω-cm) GaAs is briefly described. Initial measurements on the static and rf voltage distributions along specimens having the appropriate geometry and made from suitable high resistivity material are reported.

II. ELECTROACOUSTIC AMPLIFIERS

The work on CdS samples as amplifiers has been continued. The amplification properties of GaAs has been studied in the frequency range from 1000 to 2000 Mc. The effects of trapping are clearly evident.

III. CONTINUOUS DEFLECTION OF LASER BEAMS

An optical beam has been continuously deflected through an angle of 4° by tuning an acoustic wave in a birefringent crystal of sapphire from 1.28 to 1.83 Gc. The method is based on the change in polarization of the deflected light as compared to the incident light. The system should be capable of deflecting an optical beam through 1000 spot diameters.

INTRODUCTION

The work under this Grant is generally concerned with communication and information processing in space satellites and more particularly concerned with exploring new devices, particularly solid-state and optical devices, suitable for generation and modulation of electromagnetic waves in the microwave range and upward through the millimeter and optical frequency ranges. At present, the projects under this Grant are grouped into three general categories:

1. The use of semiconductors to produce oscillators and amplifiers at microwave frequencies in devices related to the Gunn effect.
2. The investigation of acoustic amplification at microwave frequencies by the interaction of acoustic waves with drifting carriers in piezoelectric semiconductors.
3. Parametric optical acoustic interactions, in which Bragg diffraction by acoustic waves is used to produce accurate, high speed deflection of a laser beam.

In the following sections we will briefly review the status of the projects in these three areas.

During this period one paper, prepared under the sponsorship of this Grant, was written and published:

E.G.H. Lean, C.F. Quate, and H.J. Shaw, "Continuous Deflection of Laser Beams," Appl. Phys. Letters 10, 48-51 (15 January 1967).

This paper is reproduced here in part III.

PRESENT STATUS

I. MICROWAVE OSCILLATORS AND AMPLIFIERS BASED ON THE GUNN EFFECT

A. EXPERIMENTS ON HIGH EFFICIENCY GUNN OSCILLATORS

The aim of these experiments is to determine the optimum conditions for high efficiency operation of a Gunn oscillator. The theory we have developed which should be accurate for low frequency operation, predicts efficiencies as great as 33%. This theory is based on the use of an idealized current-voltage characteristic for the device, which for practical purposes coincides with that measured and reported earlier under the present contract. We derive ideal voltage waveforms for efficient operations, and determine the required circuit to produce these voltage waveforms. One of the simplest waveforms, which is the first we are examining experimentally, is a square wave of rf circuit voltage which produces a square wave of rf current. The circuit required is a load resistor with a shorted transmission line placed across it, the line being a quarter wavelength long at the fundamental frequency of operation. With this circuit the maximum efficiency into all harmonics is 33%, with approximately 26% into the fundamental. This work represents the first theory of Gunn oscillator operation in which the predictions are substantiated very closely in practice, and thus demonstrates a fairly complete understanding of the operation of these devices in a circuit.

In these experiments a Gunn diode is placed in series with a circuit which consists of a load resistance shunted by a quarter wavelength transmission line resonant at the frequency of interest (a frequency typically very near to half the transit time frequency of the diode). This should provide a square wave voltage and current output. The function of the quarter wave transmission line is merely to provide a dc short. Thus, effectively at the fundamental and all odd harmonics, it appears as if there is a load resistance R_L in series with the diode. In this case, if we take the I-V characteristic to have the simple form shown in Fig. 1, the maximum current through the diode is the threshold current I_T and the minimum current the so-called "valley current" $I_V = I_T$. The amplitude of the square wave of current through the diode is therefore $(I_T-I_V)/2$ and the voltage across the load resistance is $R_L(I_T-I_V)/2$. If we require the voltage across the diode to be V_T , the threshold voltage, when the

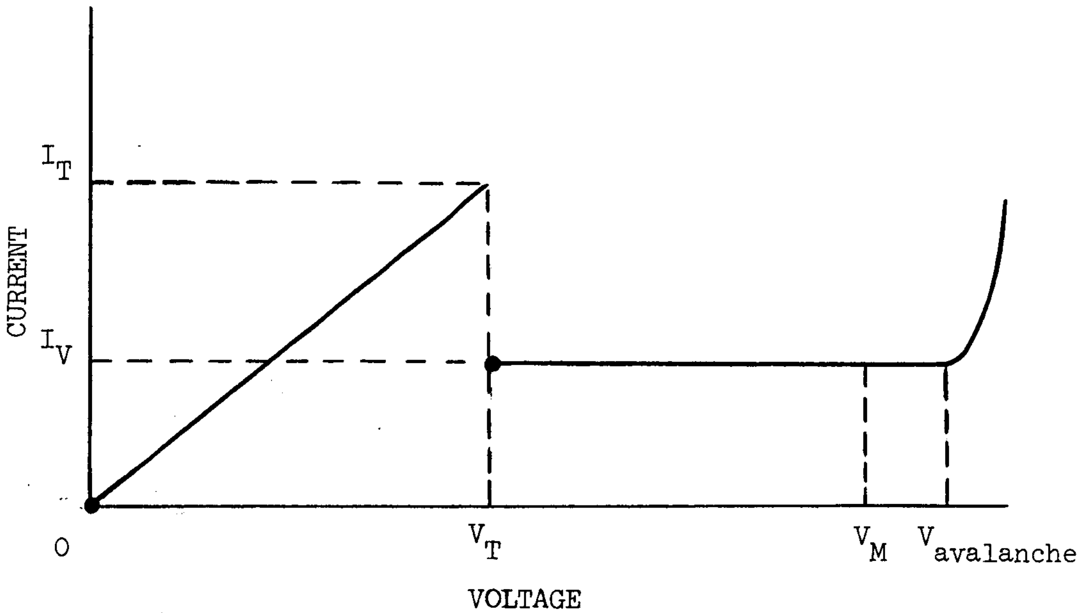

FIG. 1--Current-voltage characteristics of the Gunn diode. In an ideal diode a ratio I_T/I_V is equal to 0.5.

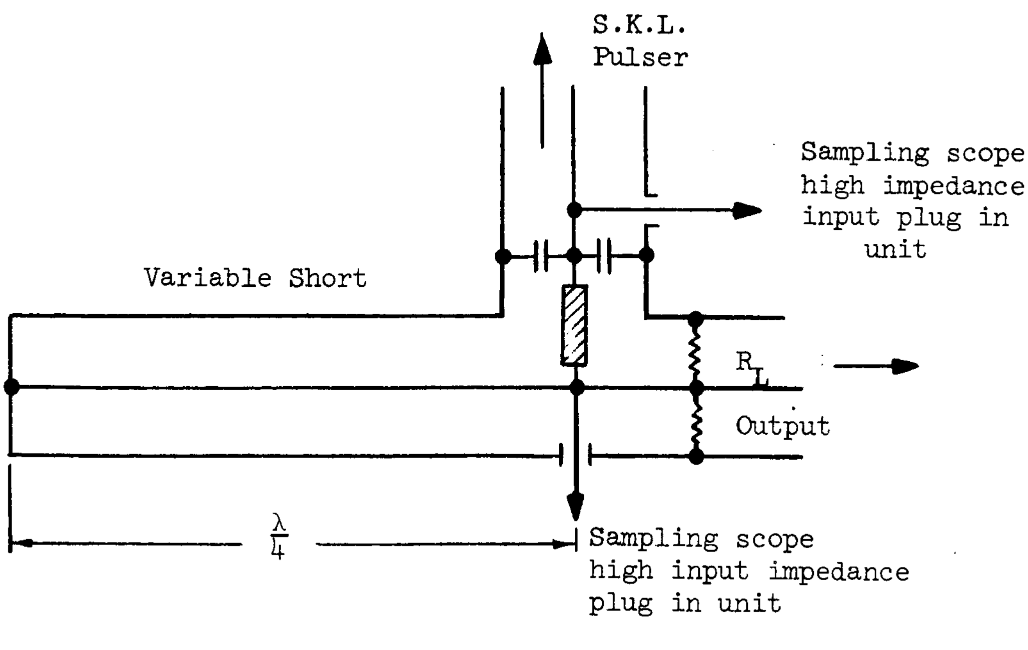

FIG. 2--A schematic diagram of the experimental circuit used.

current is I_T (the threshold current) then we may determine from these simple considerations that the average voltage applied to the diode is $V_0 = V_T + R_L(I_T - I_V)/2$. With these considerations it has been shown by Kino that the efficiency of conversion of the dc power to square wave output power is

$$\eta = \frac{1 - \alpha}{1 + \alpha}\left(1 - \frac{1}{\beta}\right) , \tag{1}$$

where $\alpha = I_V/I_T$ and $\beta = V_0/V_T$. The relationship between the load resistance, in this case R_L , and the low field resistance $R_T = V_T/I_T$ of the diode is:

$$\frac{R_L}{R_T} = \frac{2(\beta - 1)}{1 - \alpha} . \tag{2}$$

The maximum efficiency at the fundamental frequency is therefore

$$\eta_1 = \frac{8}{\pi^2}\eta = \frac{8}{\pi^2}\frac{1 - \alpha}{1 + \alpha}\left(1 - \frac{1}{\beta}\right) . \tag{3}$$

With good diodes a value of $\alpha = 0.5$ is obtainable, so that with $\beta \to \infty$ the maximum efficiency should be 33% with a possibility of 26% efficiency in the fundamental.

With similar consideration, more complicated circuits can be designed which yield a waveform that produces a voltage with a waveform like half wave rectified ac. This circuit can theoretically give an efficiency of $\eta_1 = \frac{1 - \alpha}{1 + \alpha}\left(1 - \frac{1}{\beta}\right)$ in the fundamental.

The maximum dc voltage that can be used with any circuit is limited by avalanching in the dipole domain. Typically from our experiments carried out on another contract [AF 30(602)-3595] it would appear that this avalanching voltage is of the order of 300 - 400 V in 4 ohm/cm materials and is approximately proportional to $1/n$ where n is the donor density. Thus for a sample 8 mils long with a threshold of approximately $V_T = 60$ V and an avalanche voltage of 240 V, the maximum square wave amplitude will be $1/2(240 - 60) = 90$ V and the maximum usable value of β_{max} would be $\beta_{max} = 150/60 = 2.5$. This would require $R_L/R_T = 6$, and would give an efficiency $\eta_{max} = 20$ percent, $\eta_{1max} \simeq 16$ percent.

A simple circuit to achieve this type of operation has been made experimentally using a GR mixer as a diode mount. The voltage waveform across the device was measured directly by using the high impedance probes of a Hewlett Packard sampling oscilloscope placed across the diode itself. A variable length of shorted coaxial line was used for the resonator circuit, and a resistance in one side of the T placed in series with a 50 ohm attenuator was used as the load. The voltage across this load and hence the current through it could also be measured on a sampling oscilloscope. A schematic diagram of this circuit is shown in Fig. 2. The diodes used so far are approximately 8 - 9 mils thick and have cross sections 20 × 20 mils. The low field resistance of these diodes was between 15 - 40 ohms, giving the ideal R_L to be 90 - 240 ohms. Contacts were made to them by evaporation of GeAs alloy and successive alloying at 500°C in hydrogen. The parameters of these diodes were then measured in a dc circuit before operation in the resonant system.

The most important parameter for optimum efficiency is $\alpha = I_V/I_T$. In long diodes we could fairly easily obtain a value of $\alpha = 0.5$. However, in the shorter diodes we could only rarely do this, the best value obtainable being $\alpha = 0.52$. The typical current waveform of such a diode placed in a resistive circuit is shown in Fig. 3. In Fig. 4 an example of the type of the square wave voltage waveform obtained across the load, using the same diode in the resonant circuit described, is shown. In this case the load impedance was 300 ohm. The output power of the square wave was 9.8 W and dc input 65 W yielding an efficiency of $\eta = 15.1$ percent. This is a lower efficiency than would be expected from the calculation given above because of the incorrect value of load resistance used. With this load resistance a voltage greater than avalanching would be required for optimum efficiency. In this case the maximum current obtained in the circuit I_M is lower than the threshold current I_T so that the amplitude of the square wave current and voltage across the load is less than predicted theoretically by the simple formulae given. We may define parameters $\alpha' = I_V/I_M$ and $\beta' = V_O/V_M$. In these terms the efficiency is

$$\eta = \frac{1 - \alpha'}{1 + \alpha'} \left(1 - \frac{1}{\beta'}\right) , \qquad (4)$$

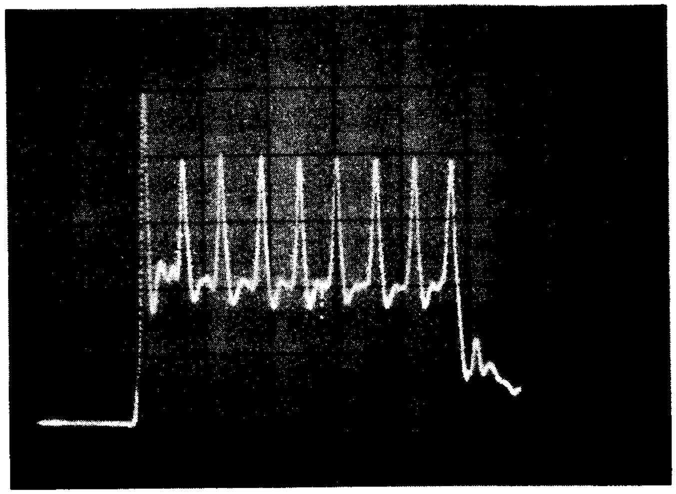

FIG. 3--A current waveform of the typical Gunn diode in the resistive circuit.

Vertical scale: 200 mA/div

Horizontal scale: 5 nsec/div.

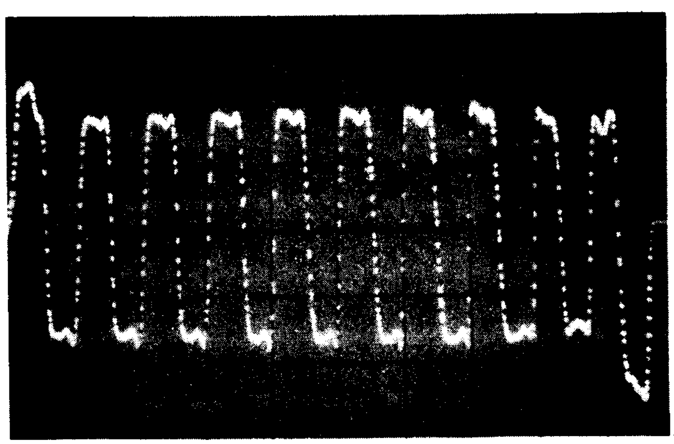

FIG. 4--An example of the square wave voltage waveform across the road impedance in the resonant circuit.

Vertical scale: 100 mA/div

Horizontal scale: 5 nsec/div.

with a load resistance R_L given by the relation

$$\frac{R_L}{R_T} = \frac{2(\beta' - 1)}{1 - \alpha'} \quad . \tag{5}$$

From the relationship

$$\frac{V_M}{I_M} = R_T = \frac{V_T}{I_T} \quad , \tag{6}$$

it follows that

$$\beta' = \frac{\beta}{\alpha}\,\alpha' \tag{7}$$

and

$$\alpha' = \frac{\dfrac{R_L}{R_T} + 2}{\dfrac{R_L}{R_T} + \dfrac{2\beta}{\alpha}} \quad , \tag{8}$$

providing R_L/R_T is such that $\alpha' > \alpha$. For the diode measured the low field resistance was 30 ohms, yielding a value of $\alpha' = 0.6$ and a theoretical efficiency of 16.7 percent, which is in reasonable agreement with the experimentally measured parameters.

We need either to use a shorter diode to obtain better efficiency, so as to increase the effective value of β , or to use the right load resistance, which as yet we have not been able to do.

Another difficulty which occurs with some diodes and which is experimentally very important is that if the contacts are not perfect, not only is the value of α affected, but also the threshold voltage is not well defined. Consequently the full voltage swing and current swing that is theoretically obtainable cannot always be obtained. We are working to improve our diodes and to obtain efficiencies greater than 20 percent with this and other circuits. So far the maximum rf conversion efficiency that we have obtained is 17.7 percent.

B. MEASUREMENT OF THE SPACE CHARGE GROWTH RATE IN HIGH RESISTIVITY GALLIUM ARSENIDE

1. Introduction

It is the aim of this project to examine possible three terminal and four terminal Gunn devices which could be used as broadband traveling wave amplifiers. The present work is concerned with using high resistivity material in which growing space charge waves can propagate without the presence of self-oscillations. So far the dc characteristics of the device have been measured, as described below; the results obtained appear to be in excellent agreement with the theory. We have begun to measure rf amplification affects, and the initial results appear to be promising.

Specimens of GaAs for which the product of length (in cm) and donor density (per cm^3) is less than approximately 10^{12} do not exhibit moving high field domains. Such specimens, however, can support a small signal longitudinal space charge wave having a group and phase velocity close to the carrier velocity ($\approx 10^7$ cm/sec) and which grows with an 'e' folding distance equal to the product of carrier velocity and negative differential relaxation time. Thus growth rates of approximately 10^4 dB per mm are possible.

In the one port amplifier reported by Thim, et al.,[1] two waves are excited. One is a space charge wave with a velocity approximately equal to the drift velocity of electrons. The other is a fast wave associated with the total current through the device; this wave has infinite phase velocity and no charge modulation. The resultant ac terminal impedance can have a negative real part close to frequencies corresponding to the reciprocal of the transit time and its harmonics. Thus reflection gain is possible. Because the device relies on this interference between the two waves it is narrow band and the coupling between the ac fields and the total current through the device is weak. This in turn leads to low saturation powers (typically - 10 dBm).

Both the bandwidth and saturation power levels can, in principal, be increased if the fast wave is not excited. Consider the situation shown in Fig. 5 where a thin film of GaAs ($\approx 100\ \mu$, e.g.) is grown on an insulating substrate. The signal is injected some distance from the cathode and coupled out downstream near to the anode contact. If the bias circuit is open circuit to ac then no total current can flow and the growing slow wave only is excited. Since to first order the slow space charge growth rate is independent of frequency and there is no interfering fast wave, the bandwidth is only determined by the coupling. The experiments

[1] H. W. Thim, et al., Appl. Phys. Letters 7, 107 (Sept. 1965).

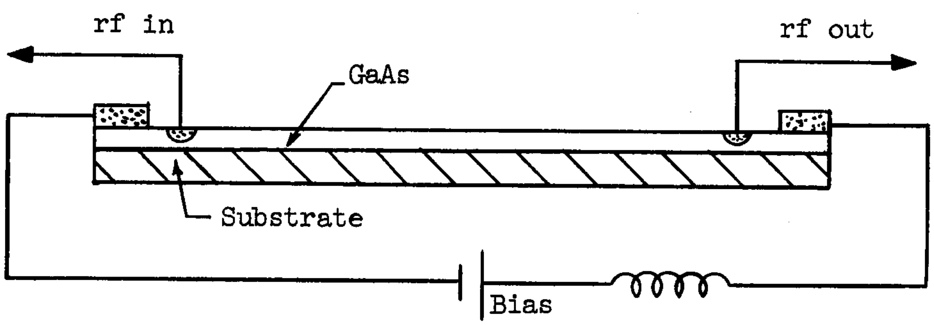

FIG. 5--Schematic of distributed amplifier.

reported here are concerned with investigating the possibility of constructing a unilateral two port microwave amplifier of this type using the transferred electron effect in high resistivity GaAs.

2. Present Status

We have chosen initially to work with specimens of about 1 mm length. In order that these should be stable against domain formation, the resistivity must be greater than about 500 Ω cm. We have worked with material of around 600 Ω cm and 3000 Ω cm, and have been able to make satisfactory ohmic contacts by evaporating gold-germanium layers about 1000 Å thick and subsequently alloying in hydrogen at 500°C for 2 minutes.

The static current-voltage characteristics of such specimens can readily be calculated by solving Poisson's equation and the current continuity equation. Using the experimental curve for drift velocity as a function of field obtained by Ruch and Kino,[2] we have computed both the current-voltage characteristics and the non-uniform field distribution that might be expected, for a range of doping densities and specimen lengths.

In Fig. 6 the measured I-V characteristics for a 700 μ specimen of 3000 Ω cm GaAs is compared with the appropriate theoretical one. The current has been observed for times varying from about 5 nsec to several millisec after the voltage was applied and no time dependent trapping or deep donor ionization was observed up to average fields of 17 kV/cm. We have been able also to measure the potential distribution along these specimens by using a fine capacitative probe, of the type first described by Gunn, drawn along one face. This probe and its motor driven probe carriage have been constructed during the reported period. In Fig. 7 the potential distribution, both theoretical and experimental for 3000 Ω cm material, is for the particular case when the average field is some four times greater than the threshold field ($E_{threshold}$ = 3.2 kV/cm). In both figures the agreement between experiment and theory is gratifying. Figure 8 shows an oscilloscope trace of the potential distribution V along the specimen for two

[2] J.G. Ruch and G.S. Kino, Microwave Laboratory Report No. 1481, Stanford University (Nov. 1966).

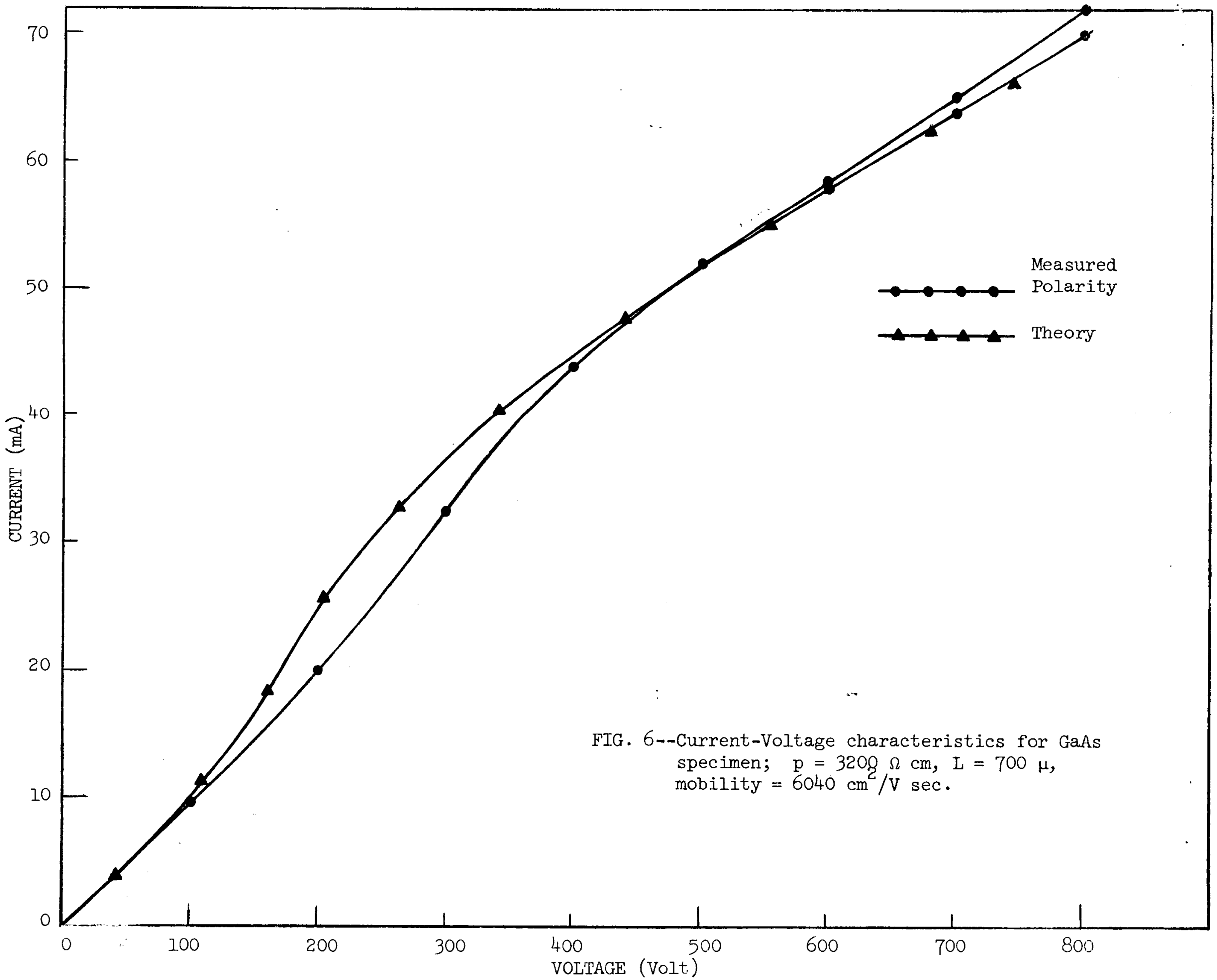

FIG. 6--Current-Voltage characteristics for GaAs specimen; p = 3200 Ω cm, L = 700 μ, mobility = 6040 cm^2/V sec.

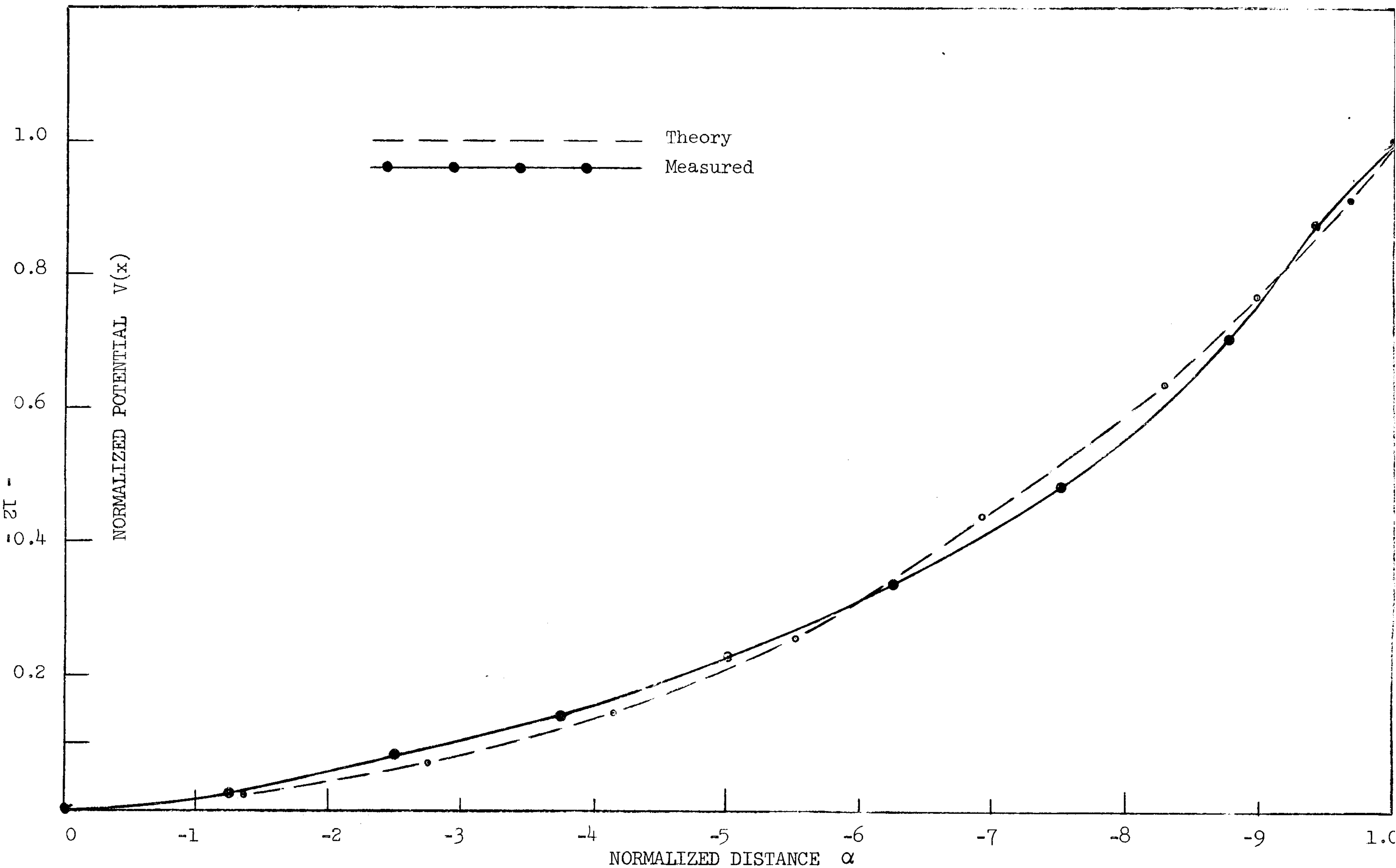

FIG. 7--Voltage distribution through GaAs specimen, average field 12 kV/cm.

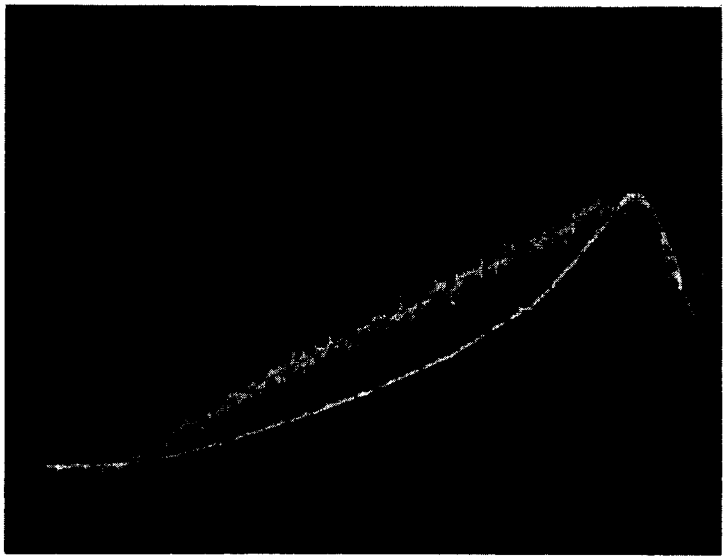

FIG. 8--Voltage distribution with distance. The sensitivities are different to show the departure from linearity in the high field case (lower curve).

values of applied voltage; the linearly increasing trace is for an average field of 1000 V/cm, the lower one for 12,000 V/cm, which implies a maximum field at the anode of the order of 25,000 V/cm. The departure of the electric field from the uniform distribution when the applied voltage is increased, can be clearly seen. Similar measurements have been performed on the 600 Ω cm material and again the agreement between experiment and theory is good.

These experiments have thus confirmed that the high resistance material used does exhibit a drift-velocity versus electric field characteristic similar to that proposed theoretically and measured in semi-insulating material.[2] They also suggest that trapping effects, which could have been present in such highly compensated material, are not significant. Moreover, we now have detailed information on the static field distribution through the specimens. This is required since the growth rate and wavelength of the small signal wave depends on the local static field.

We have started to investigate the small signal behavior by applying at 1 GHz signal in series with the bias voltage. The ac signal picked up by the probe as it traverses the specimens is observed. With this particular method of excitation both the fast and slow waves are excited. We have observed signal growth but as yet have not been able satisfactorily to separate the two components from each other. The fast wave is characterized by having no phase shift with distance whereas the wavelength of the slow wave should be approximately 100 μ. Thus by observing the phase variation of the probe signal with distance the presence of the slow wave should be demonstrable.

We intend during the next period to try and excite the slow wave alone by placing a contact near to the cathode and open circuiting the bias contacts to rf, thus eliminating the fast wave. If this scheme is successful, we shall study the coupling between two such contacts as depicted in Fig. 5.

In summary, the dc characteristics of the device appear to be very close to those we predict theoretically; trapping effects do not appear to be important in the material we are using. The rf experiments indicate that there is a growing wave present, as is indicated by our theory. Thus, if we can couple sufficiently strongly to this wave, we should be able to construct a two port broadband unilateral amplifier akin to the traveling wave tube.

II. ELECTROACOUSTIC AMPLIFIERS

At the beginning of this program we had demonstrated that photoconducting CdS crystals could produce acoustic gains at 800 Mc which were in reasonable agreement with the one-dimensional theory. The initial experiments pointed up the problems which had to be overcome if the phenomenon was to be reduced to a useful device. These were two — first, the couplers had to be improved and pushed to higher frequencies — second, the instabilities which were observed in the crystal had to be understood and methods devised for overcoming them. The work on these two problems has proceeded on other contracts and there have been advances in both areas. The insertion loss at 800 Mc has been reduced to a value below 8 dB and at 1600 Mc to a value less than 15 dB. This has been accomplished with thin films of piezoelectric material such as CdS and ZnO. The oscillation problem is now fairly well understood, and a model has been developed which is in satisfactory agreement with the experimental observations. The study has served to define the range of crystal parameters where oscillations will not occur.

In the present program we have concentrated on the problem of extending the amplifiers to the microwave region. We are continuing the work on the CdS samples as mentioned in the last report, with the effort directed toward the design of a suitable fabricating technique that will allow us to mount small samples on a proper heat sink with the acoustic transducers in place.

We find that ZnO doped with copper is now available in the proper resistivity range (100 Ω-cm) and we will study the material in our present set-up.

The primary work in this period has been devoted to GaAs. The material GaAs is an attractive material because of the intensive effort devoted to this material in connection with programs on the Gunn effect. It has been demonstrated in cw oscillators that this material will operate with a dc power density in excess of 10^7 watt/cm^3

and this feature adds to its attraction as a material for acoustic amplifiers. We have been working with n-type material with a resistivity of 1.5 Ω cm. We have studied the gain versus field for several frequencies in the region of 600 to 2000 Mc. The preliminary results are shown in Figs. 9 through 11. In Fig. 9 we plot the gain versus field at 600 Mc. We see that the behavior is in fair agreement with the theoretical prediction. In Fig. 10 we plot the gain characteristic near 1900 Mc and here we note that the measured gain is reduced by a substantial factor over the predicted curve. At the higher fields the measured gain is approaching the theoretical curve but at lower fields the discrepancy is large. Kuru has probed the field versus distance along the sample and he finds that it is rather uniform. We conclude that the contacts are ohmic and the entire sample is exhibiting gain. A clue to the behavior can be obtained from Fig. 11 where we indicate the maximum observable gain over the entire frequency range of 600 to 1900 Mc. One would expect that the gain would monotomically increase with frequency since the frequency of maximum gain for this material is above 2.0 Gc. Rather than the monotomic increase, we observe a decrease in gain and a minimum near 1400 Mc. This we believe is due to trapping effects in the bulk material. The effect has been calculated by workers in Japan and experimentally verified in CdS near 45 Mc.[1] They point out that for traps with a trapping time τ the acoustic gain will not be strongly affected in the range $\omega\tau \ll 1$ or $\omega\tau \gg 1$ where ω is the acoustic frequency. But in the range $\omega\tau \sim 1$ the traps can reduce the gain if the density of trap is appreciable. We conclude from this that the trapping time τ is less than 10^{-9} sec and this mechanism is most likely responsible for the suppression of acoustic gain in this frequency range.

The effects are more complicated than predicted from the trapping theory of Uchida, however, for the variation of gain as a function of electric field is not well behaved. We are now improving our transducers and measuring techniques so as to be able to resolve some of these difficulties.

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[1] I. Uchida, T. Ishiguro, Y. Sasaki, and T. Susuki, J. Phys. Soc. Japan 19, 674 (1964).

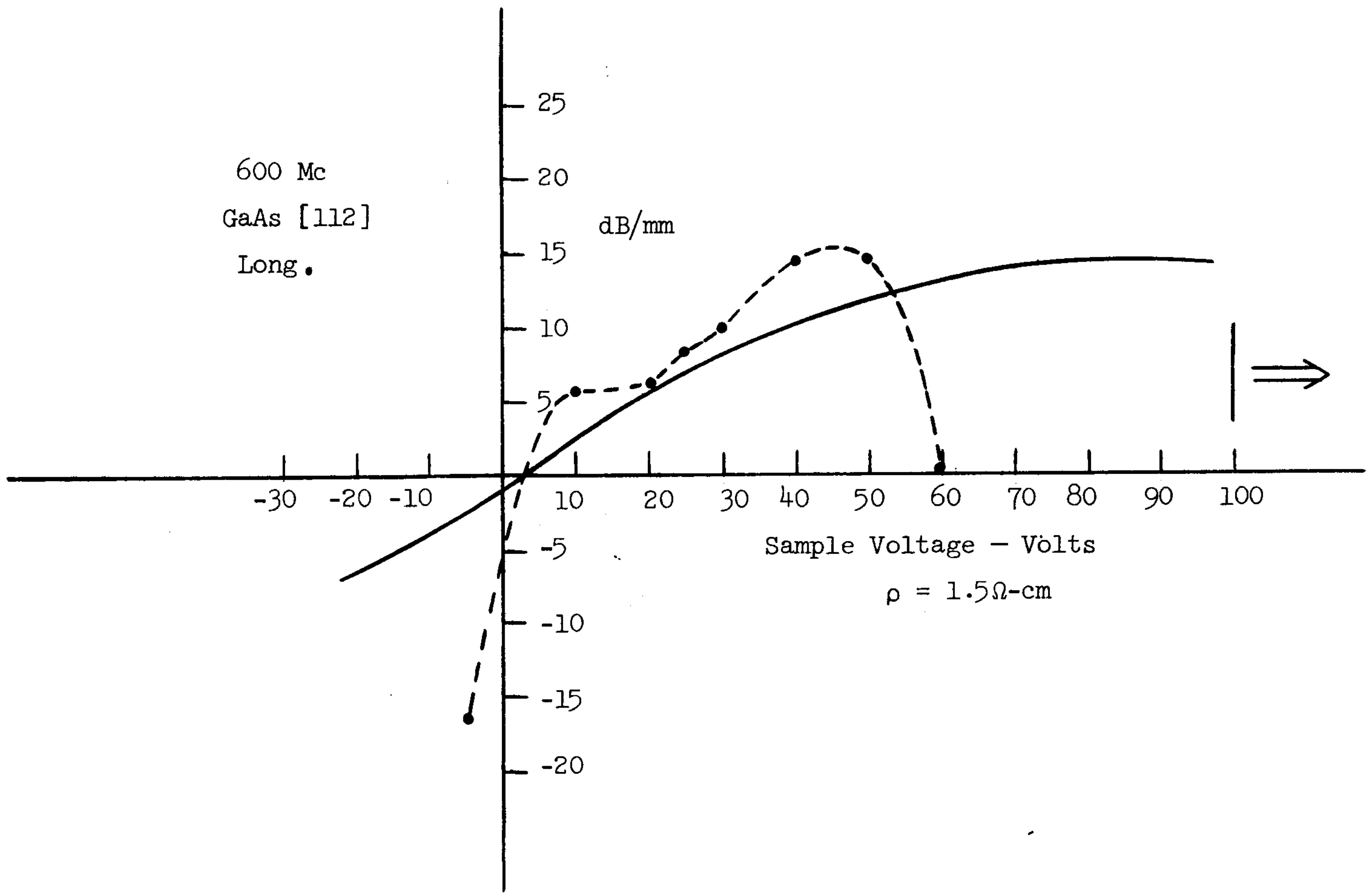

FIG. 9--Acoustic gain for longitudinal waves in GaAs as a function of applied field at 600 Mc. The dotted curve is the measured data and the solid curve is the prediction from the linear theory.

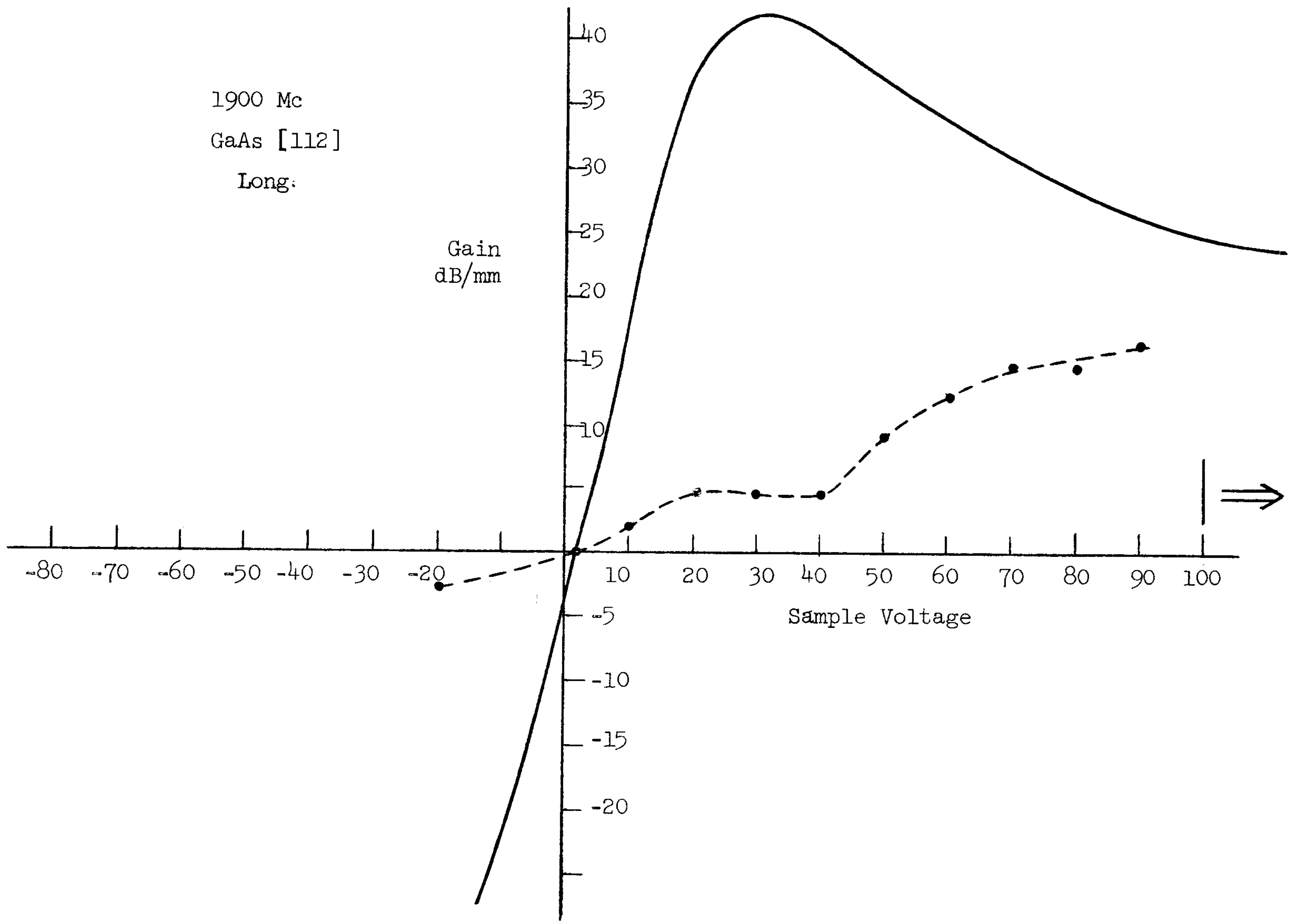

FIG. 10--Acoustic gain for longitudinal waves in GaAs as a function of applied field at 1900 Mc. The dotted curve represents the measured values and the solid line is the prediction from the linear theory.

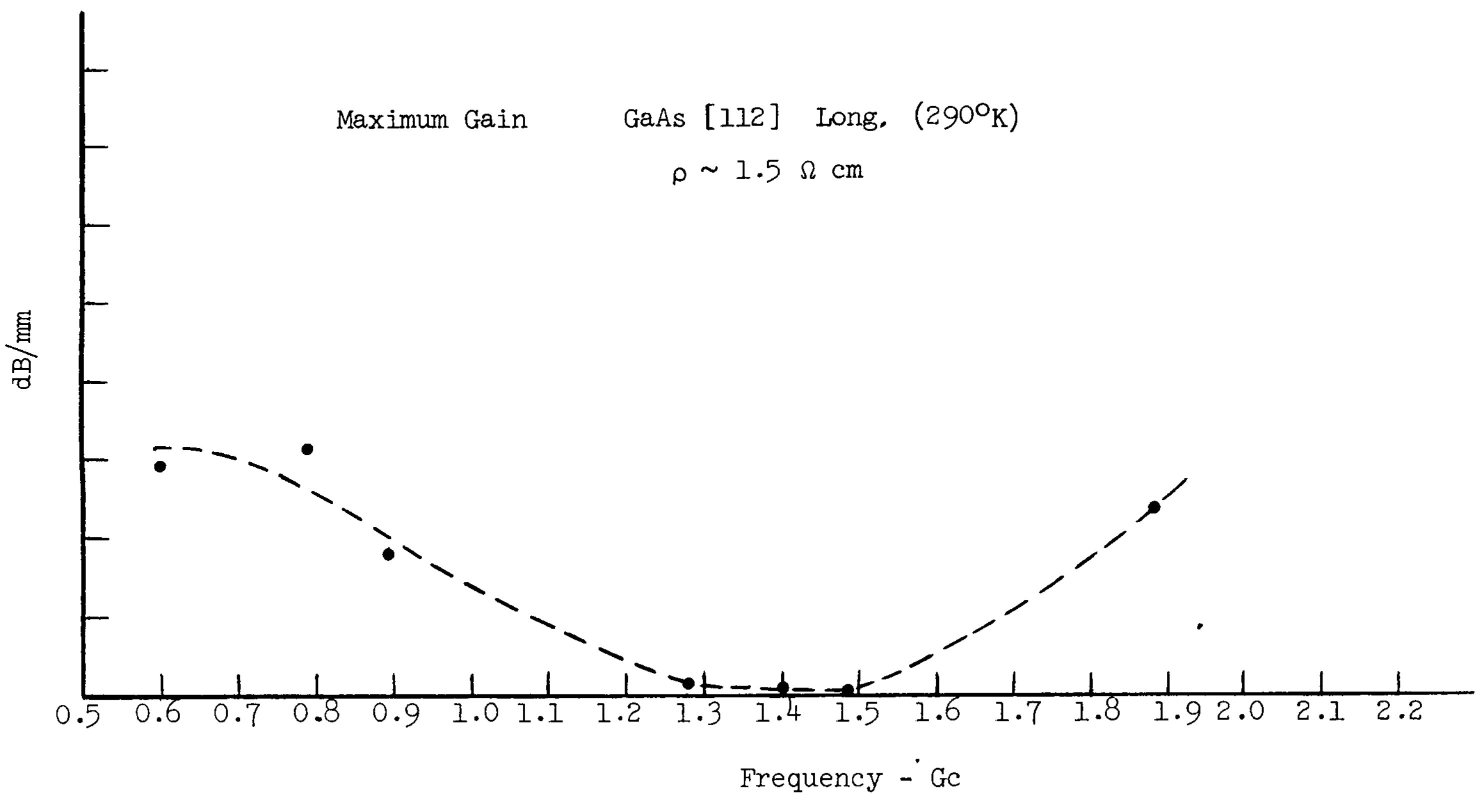

FIG. 11--The peak gain versus frequency for longitudinal waves in GaAs. The minimum near 1400 Mc is attributed to trapping centers with a trapping time near 10^{-10} sec.

III. CONTINUOUS DEFLECTION OF LASER BEAMS*

The methods of laser beam deflection and the limitations of the present systems have been reviewed recently by Fowler, et al.[1] It is clear that optical deflection systems do not yet compete with electron beams for high speed scanning and recording of information, and it is therefore worthwhile to consider alternative methods for the continuous scanning of light beams. In this letter we present a method based on the Bragg scattering of light from a sound wave in a birefringent crystal. In sapphire we have been able to deflect a laser beam continuously through an angle of 4.0° by varying a single electrical parameter – the frequency of the sound wave. This should be sufficient to resolve 1000 spot diameters.

Acousto-optic light deflectors which are capable of continuously deflecting a light beam through 200 spot diameters have been reported by Korpel, et al.[2] The light deflection was achieved by Bragg angle scattering of light from a steerable 30 Mc sound column. The principles of acousto-optic deflection of light waves has been reviewed recently by Gordon.[3] "Phase matching" is a basic requirement of this process, and requires that the vector sum of the three wave vectors add to zero, i.e., $\bar{k}_1 + \bar{k}_2 = \bar{K}$. Here K is the wave vector for the sound wave, k_1 and k_2 are the wave vectors for the incident light and diffracted light. This is illustrated in Fig. 12(a) for an isotropic medium where $|k_2| = |k_1|$. We see from this diagram that in order to shift the angle of the output light beam it is necessary to change both the direction and magnitude of the acoustic wave vector, K . In the past this has been accomplished in two ways: (1) by beam steering, whereby

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*Published under this title; see p.1 above.

[1] V.J. Fowler and J. Schlafer, Proc. IEEE 54, 1437 (1966); also Appl. Optics 5, 1675 (1966).

[2] A. Korpel, R. Adler, P. Desmares and W. Watson, Proc. IEEE 54, 1429 (1966); also, Appl. Optics 5, 1667 (1966).

[3] E.I. Gordon, Proc. IEEE 54, 1391 (1966); also, Appl. Optics 5, 1629 (1966).

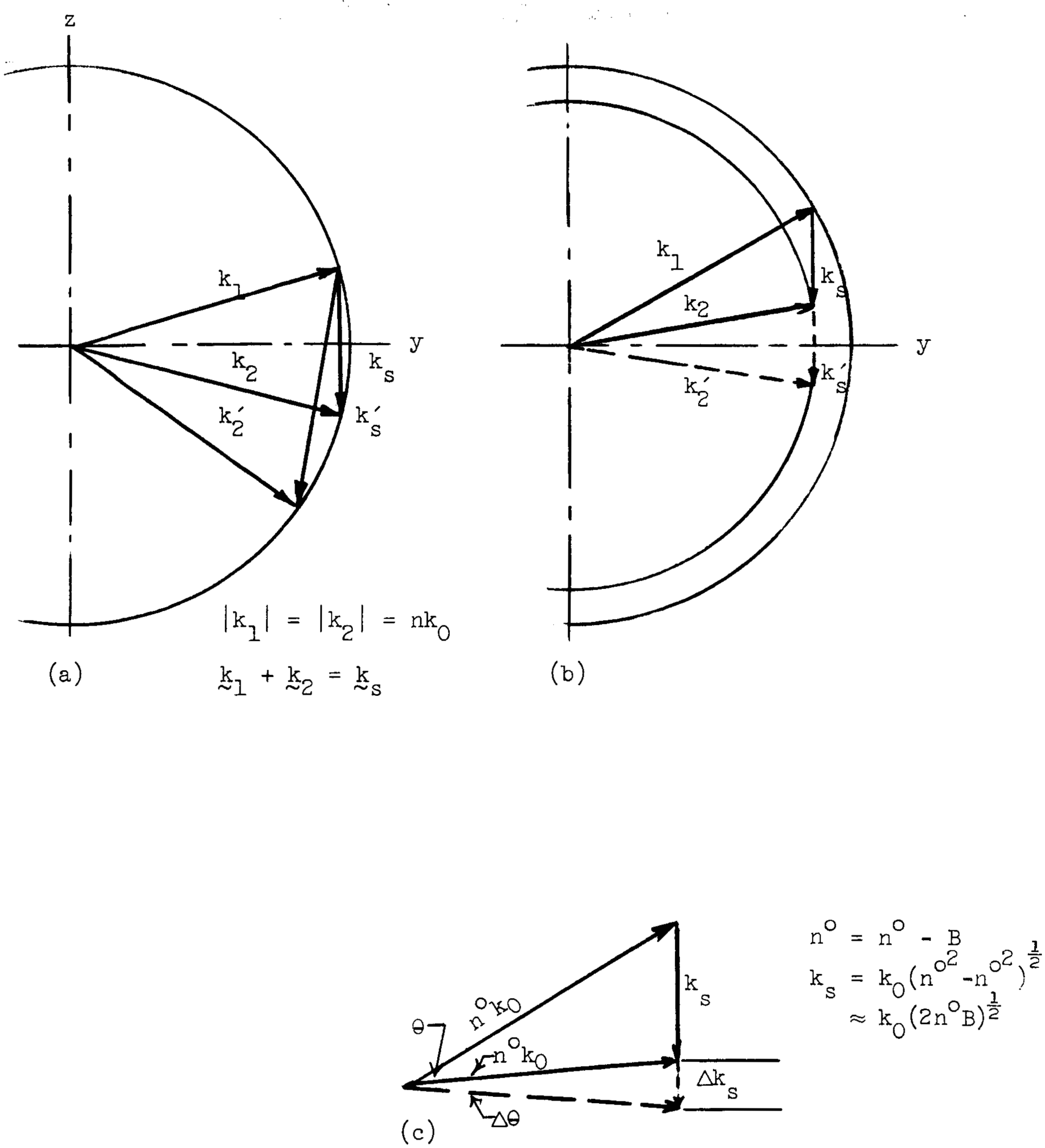

FIG. 12(a)-The wave vector locus and orientation for acoustic deflection -
(a) an isotropic crystal,
(b) an anisotropic crystal,
(c) the vector triangle for an anisotropic crystal for the special case where the acoustic wave vector is tangent to the locus of the wave vector for the extraordinary ray. The optic axis is normal to the plane of the figure. A preferable orientation would be realized if the optic axis was in the plane of the figure and parallel to the acoustic wave vector.

the acoustic column is launched from a transducer array which generates an acoustic beam with a direction that varies with frequency, and (2) by using a focused acoustic column such that the acoustic beam contains K vectors covering a cone of directions. In the latter system the light is scattered by a different portion of the acoustic column as the Bragg angle is varied. The fraction of acoustic power available for deflection is equal to N^{-1}, and therefore the system becomes inefficient as N is increased. We define N as the total number of resolvable spots.

It has been shown[2,3] that for an acousto-optic device the parameter N is given by

$$N = \Delta f \tau \quad , \qquad (1)$$

where Δf is the frequency change in the acoustic frequency and $\tau = D/v_s$ is the transit time of the sound wave across the light beam. The D is the width of the light beam and v_s is the velocity of sound. The upper value of τ is limited by the physical limitations on optical apertures and crystal dimensions. However, the value of Δf can be greatly increased if one can devise a method which utilizes a high acoustic frequency f_0, since the ratio $\Delta f/f_0$ can approach 0.5. The "beam steering" techniques become unattractive as f_0 is increased because of the difficulty of fabricating the transducer array.

We wish to report here on a method of acoustic deflection of light which is capable of deflecting the beam through an angle of several degrees without "beam steering." Referring again to Fig. 12(a) we see that the requirement that the magnitude of the scattered light vector be equal to that of the incident light vector, k_1, is highly restrictive and forces one to change both the direction and magnitude of the acoustic vector K if the relative direction of the output light beam is to be changed. In a birefringent crystal the diffracted light vector, k_2, can differ in magnitude from k_1 if the polarization of the E-vector is changed in the scattering process. Such a change in polarization is well known, and it typically involves the photoelastic constant $p_{44} = p_{55}$ if the scattering is from shear waves. Dixon[4] has reported on this type of scattering in both quartz and sapphire. He gives a clear presentation of the relations that must exist between the k-vectors.

For our purpose of light deflection we wish to consider the special case illustrated in Fig. 12(b). We have chosen the magnitude of the acoustic wave vector such that it is tangent to the wave surface for the extraordinary ray. The sound wave and the diffracted light wave are normal to each other. From the triangle of Fig. 12(c) we see that

$$K \simeq k_0 \sqrt{2n^o B} \quad , \tag{2}$$

where $K = \frac{2\pi f_0}{v_s}$ is the acoustic wave vector, $k_0 = \frac{2\pi}{\lambda_0}$ is the optical wave vector in vacuum, n^o is the index for the ordinary ray and B is the birefringence of the crystal. The value of B can range from $n^o - n^e$ for light waves traveling in a plane normal to the optic axis to zero for light waves traveling in a plane containing the optic axis. It is clear from Fig. 12(c) that a change in the direction of the deflected light vector from k_2 to k_2' can be obtained by a change in the magnitude of the acoustic wave vector from K to K' . Thus we can deflect the optical beam by varying the frequency of a well-collimated acoustic beam which remains fixed in direction. We define $\Delta\Theta_m$ as the maximum deflection angle (external to the crystal) and Θ_x as the angle of the input beam relative to the acoustic wavefronts (see Fig. 12). From Fig. 12(c) we find that $\Theta_x = n^o\Theta = \sqrt{2n^o B}$. It is not difficult to show that the intensity of the output beam will go to zero when $\Delta\Theta_m = \pm (2n^o\lambda_0/W)^{1/2}$. From this we can write

$$\frac{\Delta\Theta_m}{\Theta_x} = \pm (\lambda_0/WB)^{1/2} \tag{3}$$

where W is the width of the acoustic beam.

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[4] R. W. Dixon (to be published).

We have demonstrated this system in a standard Bragg diffraction cell[5] with shear waves in sapphire and a Ne-He laser as a source of light $(\lambda_0 = 0.6328\mu)$. Sapphire is a positive uniaxial crystal with $n^o = 1.765$ and $B = 0.008$. The sound wave traveled along the x-axis of the crystal with a velocity of 5.85×10^5 cm/sec. This is the characteristic velocity of the "slow shear" wave.[6] The light ray was normal to the optic axis with the input wave as the ordinary wave $(k_1 = n^o k_0)$ and the output as the extraordinary wave $(k_2 = n^e k_0)$. The angle external to the crystal of the input wave [see Fig. 12(c)] is given by $\theta_x = n^o\theta = \sqrt{2n^oB} = 9.66^o$ for sapphire. The acoustic frequency required to satisfy Eq. (2) is equal to 1.56 Gc and we find that $d\theta_x/df = \lambda_0/v_s = 1.06 \times 10^{-4}$ rad/Mc. The experimental results are shown in Fig. 13 where we have plotted (a) the change in angle of the diffracted beam versus acoustic frequency with all other parameters held constant, and (b) the relative intensity of the deflected beam. We note that the measured value of $d\theta_x/df$ is 1.07×10^{-4} rad/Mc . The ratio of I/I_{max} is the intensity of the deflected beam relative to the maximum intensity as obtained by adjusting the angle of incidence for the input light. The actual intensity of the deflected light did decrease with an increase in acoustic frequency, but this was a result of a decrease in sound intensity at the higher frequencies. The plot in Fig. 13 gives a measure of the scattering efficiency for a constant value of sound power. The ratio of the deflected light intensity to the intensity of the incident beam can be calculated from known expressions;[3] it depends on the material constants and upon the value of p_{55} . We have not made an accurate measurement of p_{55} in sapphire but it is estimated to be 0.1.

We can use Eq. (3) to estimate the shift in acoustic frequency which will produce a null in the output light beam since $\Delta f_m/f_0 = \Delta\theta_m/\theta_x$. In our case with an acoustic beam diameter, W , approximately equal to 1.25 mm, we have $\Delta f_m/f_0 = \pm .25$ which is slightly less than the value shown in Fig. 13. There we see that the acoustic frequency can be varied

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[5] C.F. Quate, C.D.W. Wilkinson, and D.K. Winslow, Proc. IEEE 53, 1604 (1965).

[6] J.B. Wachtman, Jr., W.E. Tefft, D.G. Lam, Jr., and R.P. Stinchfield, J. Res. Natl. Bur. Std. 64A, 213 (1960).

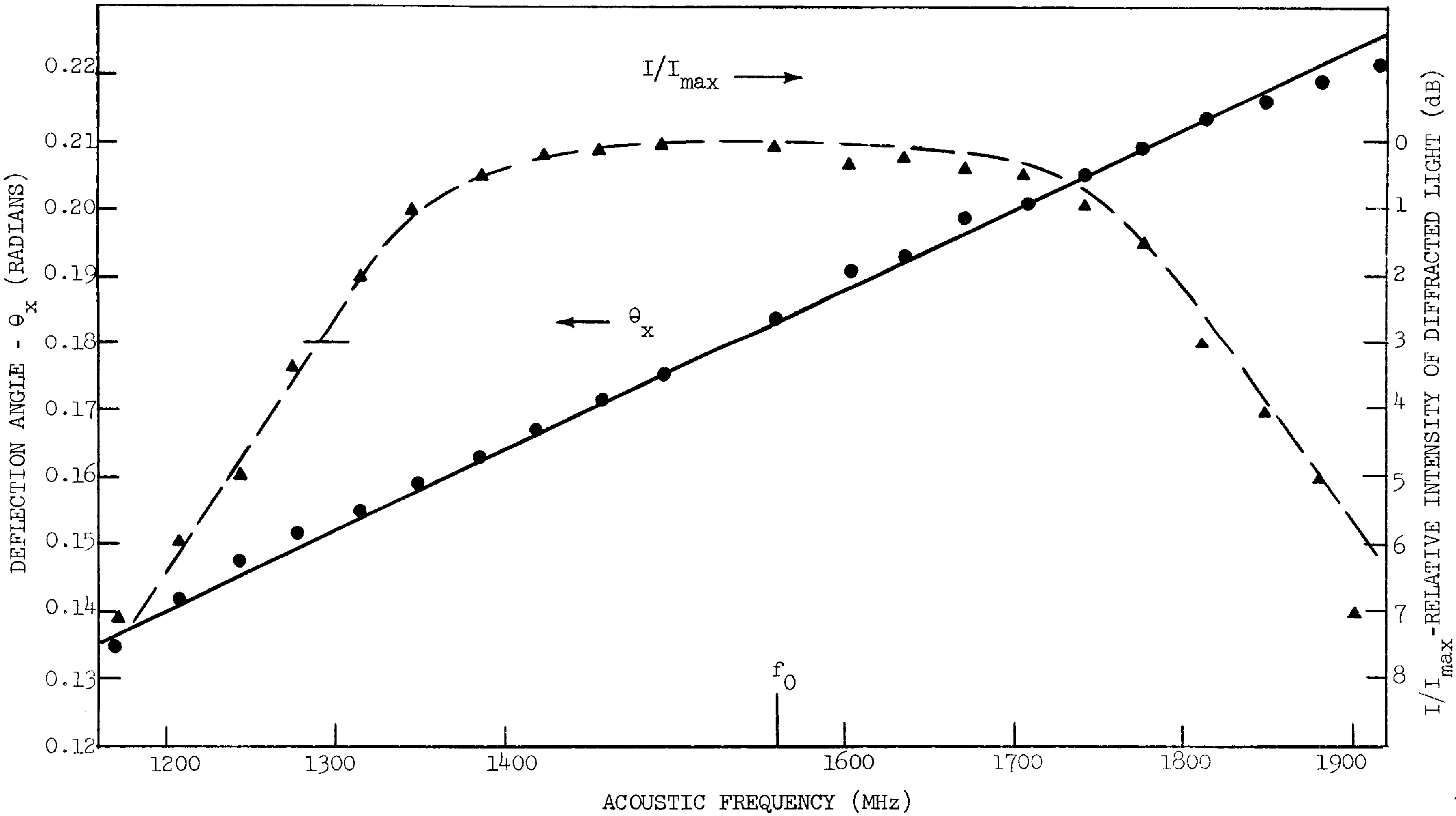

FIG. 13 --Results for beam deflection in x-cut sapphire. The θ_x is the angle of deflection of the diffracted beam relative to the input beam. I/I_{max} is the relative intensity of the diffracted beam as explained in the text. The f_0 is the acoustic frequency as calculated from Eq. (2).

by ±400 Mc without appreciable degradation of light intensity. The value of N can now be calculated. We have a measured value of $\Delta f = 800$ Mc. We assume that we can tolerate an acoustic attenuation of 3 dB in a length, D , and therefore D = 0.75 cm since the attenuation in sapphire at 1600 Mc (room temperature) is approximately 4 dB/cm. From this we have $\tau = 1.25$ µsec and it follows from Eq. (1) that $N = 10^3$.

Finally, we would like to consider the requirements for a material that would allow one to scan through 10^4 spot diameters. We assume that $\Delta f = f_0/2$ and that the acoustic attenuation is 3 dB in a distance equal to the diameter of the optical beam. The constants for $LiNbO_3$ have been measured with $n^o = 2.286$, $B = .086$, and $v_s \approx 3.6 \times 10^5$ cm/sec.[7] The value of f_0 is 3.6 Gc and therefore $\Delta f = 1.8$ Gc. We require a τ of 5.5 µsec, a length of 1.8 cm and a loss 0.55 dB/µsec which is obtainable in $LiNbO_3$ at 77°K.[8] If we tilt the plane of the optical beam so that B is reduced to a value of 6.6×10^{-3} we find that $f_0 = 1$ Gc. The acoustic loss at room temperature is 0.3 dB/µsec and the value of τ for 3 dB total loss is 10 µsec. The crystal length would be 3.6 cm and the system would deflect the beam through 5000 spot diameters.

[7] R.C. Miller and A. Savage, Appl. Phys. Letters 9, 169 (1966); also, E.G. Spencer, P.V. Lenzo and K. Nassau, Appl. Phys. Letters 7, 67 (1965).

[8] M.I. Grace, R.W. Kedzie, M. Kestigian, and A.B. Smith, Appl. Phys. Letters 9, 155 (1966).